How Can Humans Thrive and Service Satellites in a Geostationary Orbit?

Jeremy Turner

The University of Nottingham

16th Reinventing Space Conference
London 30 Oct-1 Nov 2018

BIS-RS-2018-23

How Can Humans Thrive and Service Satellites in Geostationary Orbit?

Jeremy Michael Douglas Turner
The University of Nottingham
C42 Advanced Manufacturing Building,
Jubilee Campus,
Nottingham, NG7 2RD.
+44 (0) 11574 86069
jez.turner@nottingham.ac.uk

ABSTRACT

Geostationary orbits (GEO) and geosynchronous orbits (GSO) are crowded with operational satellites, disused satellites and debris, which will jeopardise active assets and their performance (e.g. vital communication links). These orbits are also economically and militarily important, which requires a long-term plan for turning this potential hazard into a resource, by either repairing, repurposing or recycling them for use in building future spacecraft or exploration outposts. Hence, we propose The Gateway Earth GEO space station as a vital part of a comprehensive architecture-level solution to space "junk" and debris. Also outlined here are the potential servicing, repurposing or recycling opportunities there could be to create revenue streams to support the construction and further development of Gateway Earth.

In order for it to be most effective, there is a need to place Gateway Earth space station at a position where most GEO satellites can be accessed for servicing, recycling, and removal. This paper qualifies that the orbit to place Gateway Earth station in is slightly beyond GEO using a mathematical tool, which has been developed using MATLAB, to identify timings and impulse requirements for transfer orbits to and from GEO and potential extraction and insertion timings for GSO. It also highlights that there are many resources contained in the disused satellites, which are still useable, with examples of solar panels and cameras that are serviceable and/or recyclable with the potential of turning potentially hazardous objects into a revenue and resource stream. In addition there is a security risk, as access to GEO is opening up to private industries and that potentially future rogue operators/nations who could access militarily or commercially sensitive assets without authorisation, the Gateway Earth servicing facilities could provide a solution of in-orbit shredding of such equipment. In addition, some existing satellites have potential vulnerabilities to hacking that cannot be securely solved with remote software patches and Gateway Earth could provide hardware solutions to these problems by upgrading communication arrays.

KEYWORDS: Gateway Earth; debris; space debris removal; in orbit servicing; GEO; GSO; geostationary; geosynchronous; orbit; MATLAB; space station; repurposing; revenue stream; recycling; solar array; orbital synchronisation; in-orbit refueling; graveyard orbit; battery failure;.

THE GATEWAY EARTH CONCEPT

The Gateway Earth Development Group (GEDG) proposes to install a space station in a GEO much higher in Earth's gravity well compared with low earth orbit (LEO). It requires approximately 49.5 million joules of energy *per kilogram* (figure 1) more to launch Moon or interplanetary missions from LEO compared with launching from GEO. It is far more astrodynamically and economically effective to launch from GEO, and Gateway Earth can be the start and end point for interplanetary missions. Moreover, Through a public-private partnership based around models currently being developed at the International Space Station (ISS), in particular the relatively harmonious collaboration between international governmental and industry partners. Gateway Earth is proposed to generate further revenue by acting as a space hotel, an additive manufacturing/construction facility and fueling hub for interplanetary vehicles as well as a satellite farm and servicing/recycling hub. This has been well documented and justified in previous papers [1-4].

Having the Gateway Earth space station (architecture) facility in this location makes it an ideal "launching pad" for outward going robotic and crewed interplanetary missions, to any solar system destination, and a docking port for those returning. Using Gateway Earth as a construction facility will reduce the mass of launches considerably as satellites, space vehicles and infrastructure will not have to withstand launch vibrations so less mass will be required. In addition, the nose cone and upper stage diameter will no longer be a constraint on the size of the object being launched. Made in Space has already tested building one metre length struts in a vacuum [5], used additive manufacturing in micro gravity with a 3D printer on the International Space Station [6] and in parabolic flights at the Johnson Space Centre in Houston. [7]

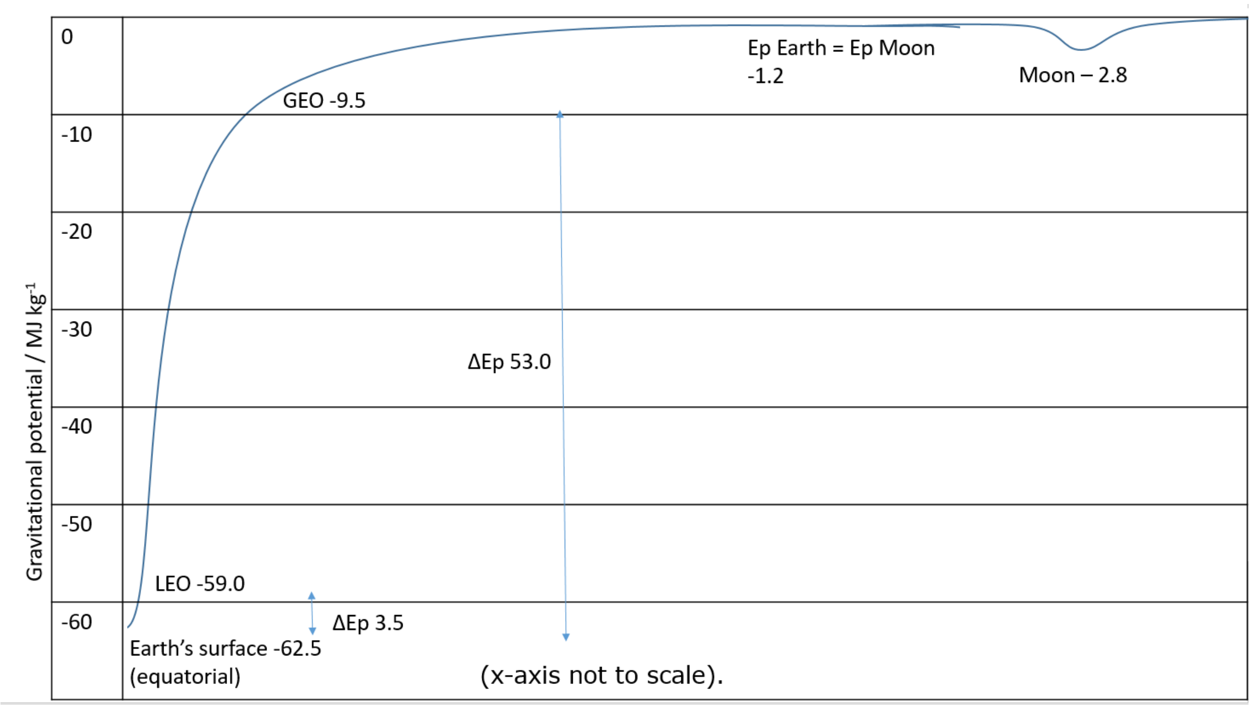

Figure 1, showing the potential wells of Earth and the Moon with energy requirements to move one kilogram from orbit to 'infinity' (x-axis not to scale).

The GEDG have conducted detailed studies into the configuration of the Gateway Earth architecture [1], potential launch schedules, logistics and internal configuration and radiation shielding. [4] All research available on the Gateway Earth website: http://www.gatewayearth.space/, as well as detailed studies into the viability and legal constraints of each of the many individual aspects of the architecture. For instance, recent research showed that further developing revenue streams through the servicing of GEO satellites makes Gateway Earth a more appealing proposition to businesses with revenues up to $40.6 billion [4].

WHERE TO PLACE GATEWAY EARTH?

The Gateway Earth space station is planned to be located in an orbit 100 times higher than The International Space Station (ISS) in GEO at ~36000km from the surface of Earth or 4.2164×10^7m from the Earth's center based on equation 1 and a sidereal day of 23 hours, 56 minutes and 4.09051 seconds. [8] After discussions with satellite manufactures I found the suggestion of putting Gateway Earth in GEO would cause additional problems with overcrowding, take up a large amount of valuable communication space and potentially strategically important space. Further research in this area was needed and this is what is presented here.

$$rGEO = \sqrt[3]{\frac{GMeT^2}{4\pi^2}} \quad (1)$$

Where rGEO is the radius of GEO

G is Newton's universal gravitational constant [9]
Me is the mass of Earth [10]
T is sidereal day length

$$rGEO = \sqrt[3]{\frac{6.6408x10^{-11} \times 5.9772x10^{24} \times 86164.09051^2}{4\pi^2}}$$

= 4.2164 x10^7 m to 5 S.F.

This work builds on the original GEO proposal to propose a more suitable orbit that will not interfere with the operations of the Geostationary and Geosynchronous Orbit satellites and their clearly defined spatial boundaries while accessing rich resource and revenue streams. GEO has over 1000 inactive satellites and countless more debris, has over 700 active satellites are in the GEO zone and they will need servicing or removing from orbit at some point [11]. The proposal is to locate the Gateway Earth architecture further out than GEO, but not too close to the graveyard orbit at 300-400km out. Here it has the potential to visit every satellite in orbit with reusable space drones, such as, Effective Space's Space Drones [12], collecting satellites and shifting their orbit to bring them within reach for orbital servicing/recycling/repurposing.

When considering locating a space station close to GEO then there are a number of considerations, most notably how close can a station be placed without causing a collision risk. Gravity variations due to the geoid [13] will change the orbit of any object in orbit however there are minimal changes in gravitational field strength due the geode at this distance from Earth, at GEO gravitational field strength (g) is 0.2242 ms^{-2} with a *maximum* variation of $\pm$ 0.031ms^{-2} (based on the maximum and minimum variations in g $\pm$ 0.7% [14]

$$g = \frac{GM}{r^2} \quad (2)$$

$$\frac{(6.67408 * 10^{-11}) * (5.9722 * 10^{24})}{(4.2164 * 10^7)^2} = 0.2242$$

$$\frac{0.007}{0.2242} = 0.031$$

This equates to a maximum acceleration due to gravity variation of 31mms^{-2} as Gateway Earth passes over GEO allowing it to theoretically be within about 200 metres of GEO without risk of collision, normal station keeping operations are easily able to counteract this small acceleration differences. In addition, the normal station keeping operations because of the higher harmonics of Earths gravitational potential (along with Moon-Earth-Sun system variations) East-West will have higher thrust requirements for GEO satellites. Active satellites will correct be able to correct anything within 100 metres with active station keeping so placing Gateway Earth in an orbit 200 metres further out from GEO should be acceptable, however some satellites have been known to have 'non-optimal' thrusts when station keeping [15] and this could make 200 metres a potential hazard. At 200 metres it would mean that, based on calculations for the MATLAB Homan Transfer Orbit tool created for this paper (available on request), it would take thousands of days (figure 2) for Gateway Earth to synchronise with non-coplanar satellites (half a GEO orbit). To ‘reinsert’ any GSO satellite back into its orbit after this length of time is clearly not satisfactory, so where should Gateway Earth be placed?

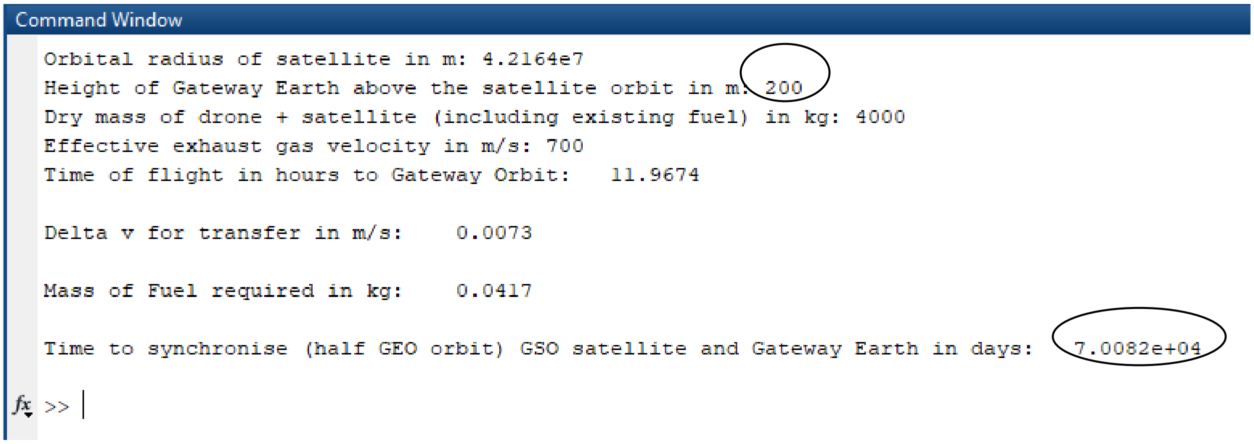

Figure 2, MATLAB screen shot showing Gateway Earth synchronisation time at 200 metres away from GEO.

Whilst a theoretical value of 200 metres away from GEO is acceptable, a ‘near miss’ of 335 metres caused the whole ISS crew to prepare for rapid departure in June 2011 then a 200 metre distance between Gateway Earth and GEO is completely unreasonable. [16] Now crucially the GEO protected region designated as regions covering an area ‘swept out’ from the GEO as $\pm$200km and making an angle of $\pm 15^{o}$ through the centre of the Earth (figure 3). These are defined as Geosynchronous Regions and any activity in this this region needs to ensure safe and sustainable use. [17] Authorisation will be required to operate in this region and very tight mitigation protocols will have to be drawn up when carrying out servicing/repurposing/recycling activities. However if it is deemed Gateway Earth will have to located outside of this region then the capture and re-deployment times will be increased and it will then run into the issue of being too close to the ‘graveyard’ orbit. I believe working with the Inter-Agency Space Debris Coordination Committee (IADC) to create suitable mitigation protocols will allow operations inside the protected region.

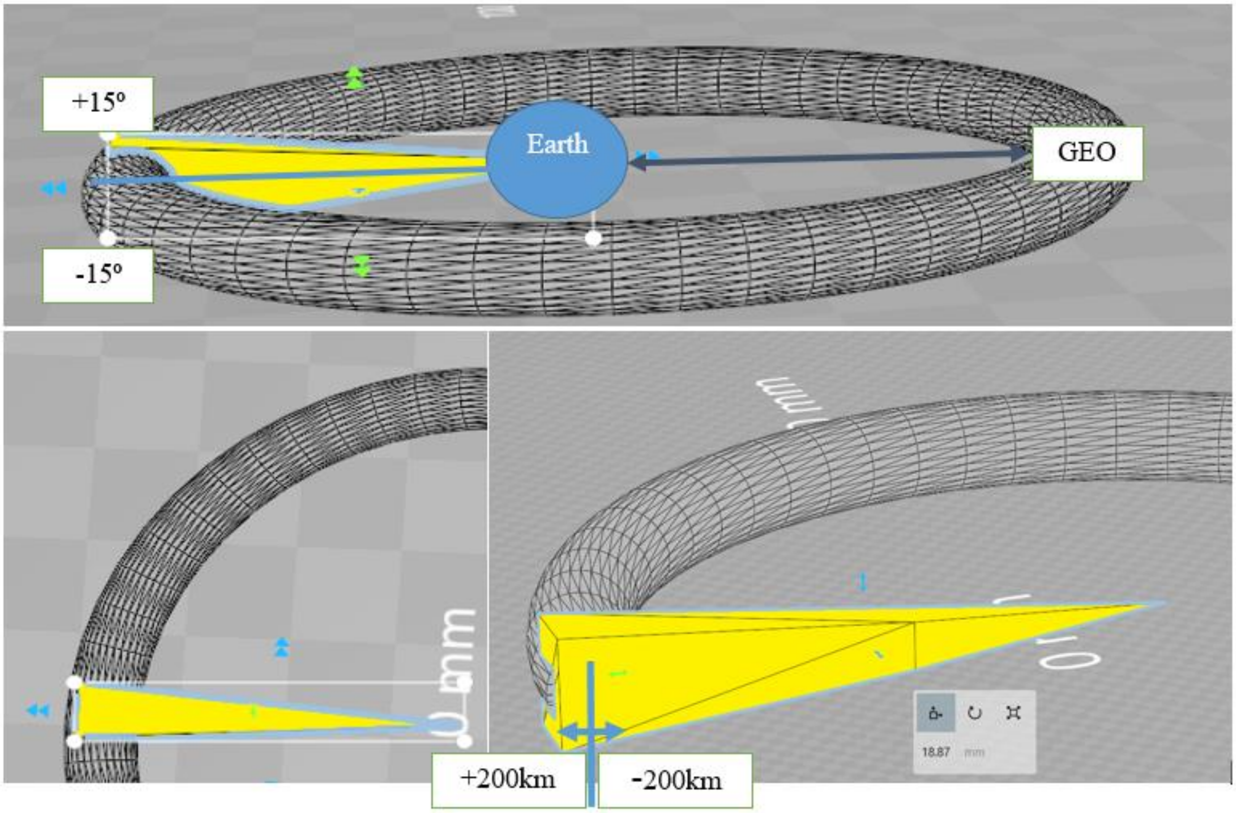

Figure 3, protected GEO region (not to scale).

It is proposed that the orbital position of Gateway Earth should be at the mid-point between GEO and the graveyard orbit beyond GEO. Gateway Earth can be positioned inside the protected zone as it will not be overtly affected by the minimal changes in gravitational field strength due the geode. After various different orbital scenarios were considered and inserted the MATLAB Homan Transfer Orbit tool placing Gateway Earth 150km away from the closest graveyard orbits and 150km from GEO seemed the best solution. It will have access to the 700+ GEO satellites and the >1000 satellites in graveyard orbits, [17] GEO satellites and Gateway Earth would synchronise ~1.9º earlier every orbit meaning that satellites could extracted for servicing and reinserted without long term forward planning. Figure 5.

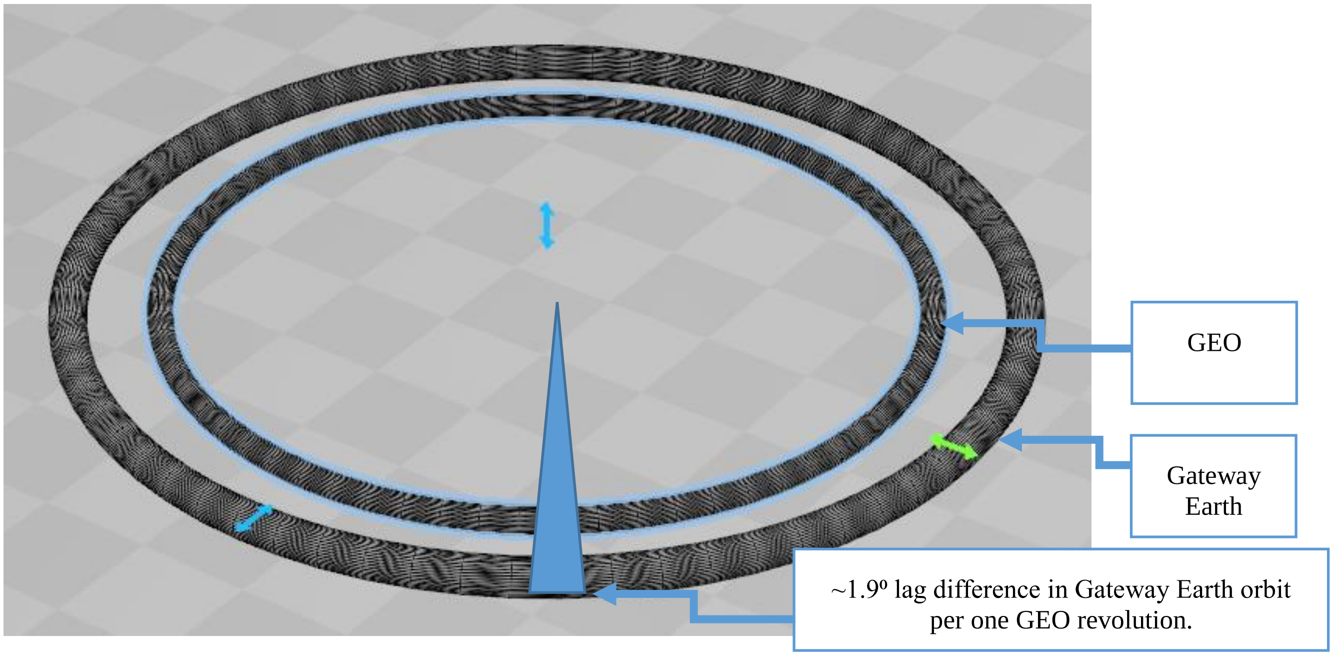

Figure 5 showing the GEO and Gateway Earth orbital lag (not to scale).

Because of this higher orbit Gateway Earth will travel more slowly over a larger circumference, this means that for every one orbit of a GEO satellite it will be a certain distance behind, Figure 6. I added this calculation to the MATLAB calculation tool to calculate the *minimum* time it would take to extract a satellite from GSO and then reinsert it into a similar orientation. This would be after half a GEO orbit in distance and would be 94 days at 150km from GEO, figure 6 & 7. The lower acceleration due to gravity and the larger circumference orbit means that Gateway Earth travels slower and further, so in one day there is a significantly larger lag at a 150km higher orbit compared to the 200 metre higher, orbit drastically reducing synchronisation times. This would require medium to long term planning to execute extraction, servicing and reinsertion, these transfers would have higher delta V values and be more complex, however these transfer calculations are well known and used. For the majority of GEO satellites no major Z axis corrections will be needed, there are a significant minority of satellites that lie within the protected ± 200km zone of geostationary orbits so extra fuel and time requirements will be needed. In addition, satellites in graveyard orbits exceed this ± 200km zone but could still contain valuable resources or potentially be re-entered into service by servicing/upgrading. At 150km further out from GEO then Gateway Earth will be able to access these resources and start the long job of clearing debris from GEO charging the owners for this service.

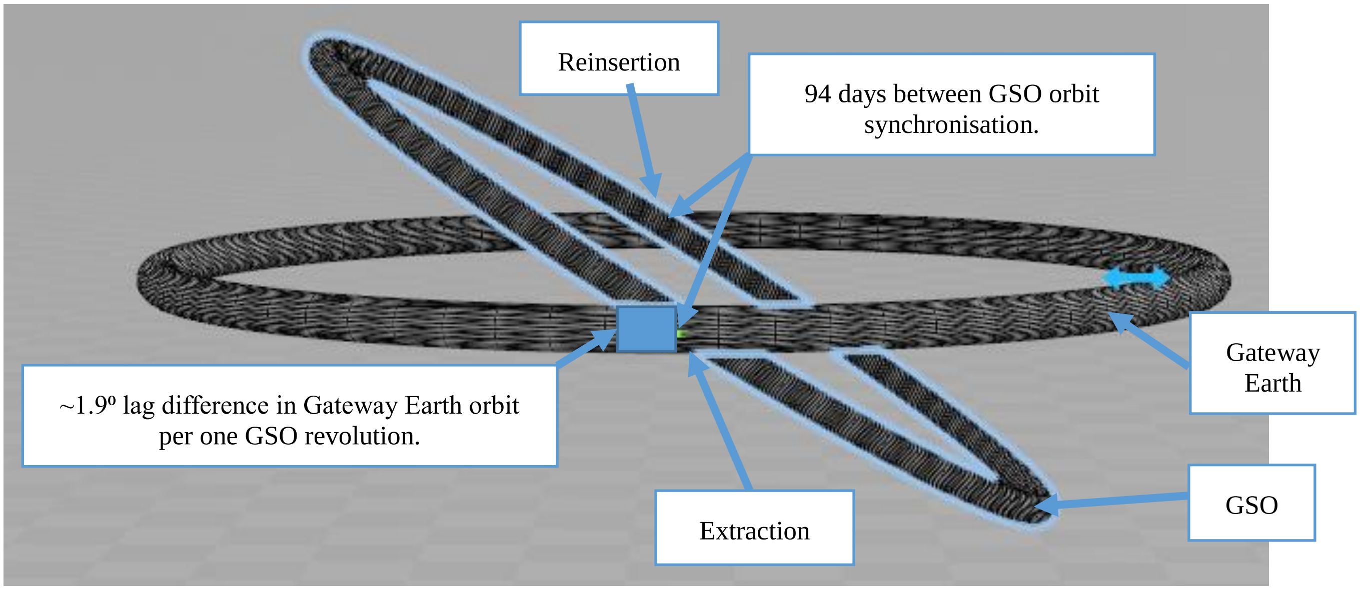

Figure 6 showing the GSO and Gateway Earth orbital lag (not to scale).

```
Command Window
Orbital radius of satellite in m: 4.2164e7
Height of Gateway Earth above the satellite orbit in m: 150000
Dry mass of drone + satellite (including existing fuel) in kg: 4000
Effective exhaust gas velocity in m/s: 700
Time of flight in hours to Gateway Orbit:   11.9993

Delta v for transfer in m/s:    5.4545

Mass of Fuel required in kg:   31.2903

Time to synchronise (half GEO orbit) GSO satellite and Gateway Earth in days:   93.8583

fx >>
```

Figure 7 Screenshot of MATLAB command window for 150km from GEO and with an average 700ms^{-1} effective exhaust gas velocity for a typical chemical rocket engine.

Homan Transfer Orbit trajectory, figure 8, based on two chemical propulsion thrusts have been calculated, the same transfers can be achieved with ion engines with a constant thrust but over longer time-periods. This would not affect operations as long term logistical planning will ensure time is allocated to these transfers. At 150km the transfer time from orbit to orbit will be ~12 hours based on an average effective exhaust gas velocity (ve) of 700ms^{-1} for chemical rocket engines.

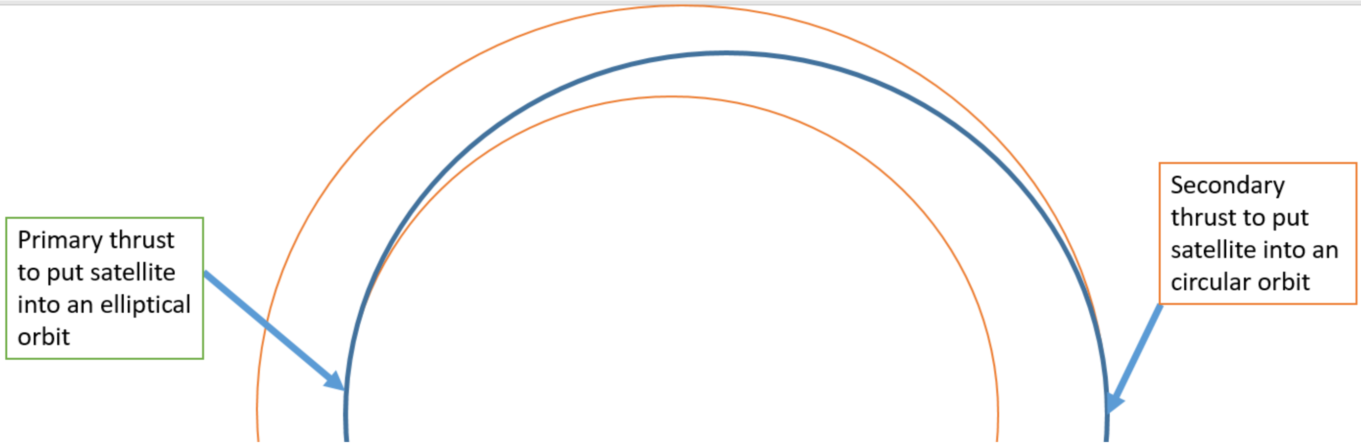

Figure 8, Homan Transfer orbit from GEO to Gateway Earth (not to scale).

As delta V calculations work for both increasing and decreasing orbits then the MATLAB calculation tool can be used to show that space drones could transfer ‘dead’ satellites from the graveyard orbit to Gateway Earth. This would be the same time and fuel requirements as the 150km from GEO and slightly longer for 250km further out. Some of these could be rejuvenated and put back into service, and where this is not the case then the materials and components will be repurposed or recycled as stated earlier. This resource and revenue stream [4] would be secondary to the main aim of debris removal and servicing of GEO satellites. It does exemplify again that having a space station servicing facility 150km above GEO will have a revenue and resource stream that will be sustainable for many years and strengthens the case for a permanent facility to create a sustainable interplanetary future for Humanity.

When creating the MATLAB calculation tool it was always intended to provide idealised values and made assumptions that it would not be used as an accurate predation tool. However the values quoted are sufficiently accurate to start planning where Gateway Earth should be placed and gaining funding for further planning/testing of equipment/hardware. I added the Tsiolkovsky Rocket Equation, in its rearranged form, to give approximate mass of fuel requirements for the transfer showing the fuel requirements are quite low: For a typical 4000kg [18] GEO satellite the fuel requirements for a chemical engine drone or satellite would be 31kg (ve ~700ms^{-1}), and for an ion engine 7.5kg (ve~2900ms^{-1}). This is based on the legendary 1903 paper (but in English here [19]) so will again be an approximation, albeit a good one.

MAKING THE CASE FOR THE GATEWAY EARTH ARCHITECTURE BEING THE MAIN SERVICING FACILITY AT GEO

Around 20% all payloads need dealing with as a matter of urgancy as only 90% of recently reaching end-of-life satellites in the GEO protected region attempt to comply with the space debris mitigation measures and only around 80 % of them do so successfully! [20] Also there is an increasing amount of ‘dead’ or ‘zombie’ satellites that are at best just an orbital hazard drifting or at worst interfering with communications and broadcasting of financially sensitive (or militarily sensitive), for example Galaxy 15 in 2010. [21] With this in mind the case for Gateway Earth being the facility for servicing satellites, collecting dead satellites and debris reuse and removal has **never been stronger** as there is a direct mandate from the IADC:

‘Each agency (and its contractors) may assign a group or individual bearing responsibilities to study, plan, implement, and review space debris mitigation activities. **The assigned group or individual should be provided with enough authority and resources required to accomplish and fulfil this duty…’** [18]

Gateway Earth is ideally placed to fulfil this role, IADC works with all the main players in GEO operations so would be the ideal template for everyone working together to clean up GEO and GSO. As space salvage is not allowed by law then the spirit of cooperation will be required and a legal framework drawn up. I believe suitable agreements between nation states and companies can, and must, be put in place to circumvent the law on space ownership from the United Nations, which essentially states everything launched into space is the property of the person who made it [22]. However technicians on Gateway Earth will have to have the highest standards of integrity and be impartiality when it comes to the 'shredding' of any sensitive military or commercial equipment. There are already integrity protocols scattered across industry for technicians working in this way and I believe any parties concerns could be dealt with, the alternatives are so concerning that a framework will be found.

The importance of GEO satellite servicing was recognised as early as the 1990's by ESA in their Geostationary Servicing Vehicle (GSV) study. [23] They realised that even for basic repairs they would need; *a capture tool, docking/rigidisation tools, close-up inspection equipment, two-finger gripper, cable/pin cutter and a leaver* (minimum requirements) and anything unforeseen happened then the mission would most likely fail. A Human has a significantly higher probability of success, and with the latest additive manufacturing technologies successful servicing, recycling/repurposing of materials and technologies is highly likely, space drones will be used for any satellite that cannot be used/repaired/broken down to move them to graveyard orbits. Many of these satellites are drifting to areas of mass concentrations on Earth that cause local gravitational wells, in particular approximately 75° East and 105° West. [21] These areas are a rich source of revenue stream for either repairing or recycling/repurposing of these satellites.

How to make use of GEO and graveyard orbit resources and create revenue streams

Space debris removal will be a paid for service that will scale with mass, orbital inclination and stability of the satellite/debris that is required to be removed, the more difficult the retrieval then the higher the cost. This service will either be a revenue stream from groups or countries not directly involved in Gateway Earth or as part of the subscription service for those involved. As a subscription service then servicing could be a 'parts only' subscription or an 'all-inclusive' subscription. The military and commercial contracts would have to be written in such a way as no commercially or militarily sensitive equipment would be reused and Gateway Earth would provide a 'shredding service' to prevent rogue nations and/or private companies from gaining access to this equipment.

One of the most accessible components of satellites are the solar panels, these will be used to create solar arrays for Gateway Earth and provide power for constructed or repurposed spacecraft. Studies have been carried out to ascertain how the efficiency of solar panels in LEO and GEO degraded over time and it is surprising little. LEO panels have been analysed on orbit and returned to Earth, ISS solar arrays decreased at 0.15% and 0.45% per year GEO satellite studies have shown a higher 0.8% per year decrease in efficiency but this still leaving the efficiency after 15 years above 24%, perfectly acceptable for our requirements. [24]

That said though solar array failure in GEO and accounted for up to 50% of the failures of GEO satellites (2004) and the majority fail within two years. [25] While this might seem on face value as having a negative impact of the reuse and repurposing of solar panels it is actually a servicing opportunity for Gateway Earth. If the only parts that have failed are the solar panels or power regulators these will be some of the easiest components to replace.

In addition the cost of solar panel failure has been estimated at $4.4 billion for a fifteen year period**,** many of these failures are relatively simple fixes for human technicians. Actual solar panel failures only account for 1/3 of the failures reinforcing that many of the power system failures out there are repairable and capable of generating a large revenue stream as up to 2/3 of the solar panels are potentially still capable of generating significant power. [26]

If solar panels were repurposed and used in the construction of Gateway Earth then savings could be made in construction and once Gateway Earth was fully powered then repurposed solar panels will create a revenue stream. These can be used on new drones, GEO orbital spacecraft, interplanetary craft and bases. With the data on solar panels and arrays being particularly commercially sensitive companies tend to display 'bare bones' values for panels rather than in-orbit figures, they do have a case for this as the power and structural integrity requirements will vary widely with application. Using that data for the latest solar panels and older data from ISS savings can be calculated:

Example cost for launching to GEO per kilogram from SpaceX are $62 million Falcon 9 for 8300kg GEO ~£5752 per kg and $90 million Falcon heavy for 26700kg GEO ~£2596 per kg. [24] The power requirements for Gateway Earth using ISS power requirements as a model will be ~ 100kW. [27] Power per kilogram 'estimates' from the more modern Spectrolab (Boeing) panels are ~350Wm^{-2} and ~2kg m^{-2} [28] however this is not the complete panel with coverings and power couplings so at least double this amount, 4kgm^{-2}, would be an absolute minimum. There is a potential that new lighter and more advanced technologies have increased efficiency and reduce the mass requirements but the stated data still appears to be on the low side.

$$\frac{100000}{350} = 285.7$$

So ~286m^2 of solar arrays required to power Gateway Earth based on these data and assumptions, however the actual ISS solar arrays are nearly ten times this area at 2500m^2 [25], and some, unverified, sources put the mass of the ISS solar arrays at ~77000kg. All the flowing calculations are based on lower mass estimates and lower launch costs.

$$285.7 \; x \; 4 = 1142.9$$

So Gateway Earth will require ~1143 kg of solar panels required based on low mass assumptions.
Northrop Grunman UltraFlex arrays are roughly similar mass to power ratios [29]. The *launch cost* savings involved are around £3 million to £7 million *not including* the cost of the panels/arrays, however this could be up to £30-£70 million using ISS's larger array values based on other launch operators having significantly higher launch costs and the solar arrays having optimistic power per kilogram published. While initially this may seem a small amount there will potentially be over a thousand solar panels working at ~25% efficiency that will create a revenue stream and this is just for one component.

Power regulation will be isolated from main systems and can be run independently with easy cut off systems in case of faults. The ISS power regulators, like one of the upgraded versions which was replaced by Tim Peake and Tim Kopra in 2016, [30] would appear to be the logical choice for Gateway Earth however there have been problems (this one in particular was linked to a single failed capacitor). The newer power regulation systems developed by ESA/NASA for the Orion spacecraft and propulsion unit will, hopefully, be more reliable and suitable for Gateway Earth. [31]

What other components are available?

Lists of resources on the Observing Systems Capability Analysis and Review Tool (OSCAR) database [32] are extensive and include; radiation measurement systems, spectrometers for a vast range of wavelengths, magnetometers, cameras covering IR to gamma rays and communication arrays to name but a few. One particular area of scientific interest worth exploring is detecting exoplanets, the detection and tracking of Near Earth Objects and Earth observation, proposed here an idea that has been used on Earth:

Cameras from satellites with the same or similar specifications, from the GOES class of satellite for example, could be combined from a group of cameras with the same imaging system to perform interferometry, this can be used to sell imaging services of earth observation or add to studies of exoplanet research and detection of Near Earth Objects. Using the SuperWASP (Wide Angle Search for Planets) international consortium's robotic telescope as a template, the light gathered by eight, or more, cameras can be combined to form an interferometer that will have a significantly higher resolving power than an individual camera. [33] Using the GOES satellite imagery group of satellites is a good case as an example, the inactive GOES 8-11 has an optical imagining camera capable of 1 km resolution at GEO in the visible spectrum and 4km resolution in the infrared (IR) region, this equates to an angular resolution of for visible light of:

$$\theta = \sin^{-1}\left(\frac{1}{36000}\right) * 3600$$

$$\theta \approx 5.7''$$

And for IR:

$$\theta = \sin^{-1}\left(\frac{4}{36000}\right) * 3600$$

$$\theta \approx 23''$$

While these resolutions may not be astronomically ground breaking, The Hubble Space Telescope has a visible angular resolution of ~0.1'', as an interferometer with a wide field of view they would be ideal for exoplanet studies, the architecture of these cameras is similar and this class of satellite is not in short supply. Use of these types of cameras as star trackers for navigation and station keeping would also be achievable.

Graveyard orbits are actually not a solution

Orbital ATK, Effective Space, the US Defense Advanced Research Projects Agency, ESA, NASA and others all talk about graveyard orbits as a solution, graveyard orbits should only be considered as a last resort. This orbit lies between 300-400km beyond GEO and is effectively an abandoned junkyard with no caretaker. As already stated use of the authors MATLAB tool shows the transfer times and this can be from graveyard to Gateway Earth. It still does not resolve the issue of leftover fuel and unstable batteries if these are truly 'dead' satellites. Eventually the graveyard will get full so without a real solution we are just kicking the can down the road.

Is in-orbit REFUELING really a safe option?

The Effective Space, Space Drones are launching in 2020 to GEO and are starting the life extension of GEO satellites. [12] After correspondence with Effective Space it has been established that their life extension drones have the required technology to deliver satellites to Gateway Earth. The hazards of re-fueling satellites by some companies and have either not been fully risk assessed or the risks have been downplayed, typical fuel valve lives are up to 16 years and 40 cycles. [34] Fatigue from operational vibrations, bombardment from cosmic rays and solar radiation will have taken their toll so those quoted figures may be significantly less. I am concerned enough to suggest halting plans to refuel satellites because after refueling a ruptured fuel line or sticking valve could cause impulses that could send satellites out of control or worse cause a catastrophic failure. This is why I advocate the use of space drones for life extension of GEO satellites with low fuel concerns and then transfer to Gateway Earth for servicing. In addition satellites thrusters degrade over time and if something as 'routine' as station keeping is performed with a degraded thruster response then more complex orbital corrections will be required involving; new modelling of orbit corrections, extra monitoring of angular momenta and a rise in staff hours required to complete the orbital corrections. [15] If the concern over fuel storage, fuel lines or thrusters is high by anomalies reported from ground control or from drone inspection regarding fuel issues then it is recommend that moving satellites to distant graveyard orbit should be the solution.

Are batteries the understated threat in in-orbit servicing?

The main concern with servicing satellites is battery condition, The Defense Meteorological Satellite Program (DMSP) - F13 satellite exploded in orbit on 3 February 2015 due to a catastrophic battery failure in Sunsynchronus orbit. [35] There have been concerns raised that this class of satellite has an inherent defect in the battery construction. The debris of this failure were tracked in real time and were shown in the Spaceflight Now article [36].

With catastrophic failure of batteries being potentially the most hazardous part of servicing and recycling satellites then discharging the batteries as much as possible must be completed before they are delivered to Gateway Earth. Another alternative is the solar cells can be remotely disconnected, in the case of satellites that are beyond repair then severing of the connecting wire (studies will need to carried out to ensure this did not produce anomalously high currents and battery failure). Batteries are significantly less likely to suffer this kind of failure if the batteries are discharged, but charged ones can quickly fail if ruptured. If the condition of a battery cannot be ascertained then the space drone will be used to orient the satellites solar panels out of sunlight to discharge the battery as much as possible. Estimates of the time required to do this will assume a full charge and minimum power drain. Again, if there is any doubt about the battery then a high graveyard orbit must be the answer.

CONCLUSIONS

With around 90% of all payloads recently reaching end-of-life in the GEO protected region attempting to comply with the space debris mitigation measures and only around 80 % of them doing so successfully the final 20% need dealing with as a matter of urgancy. [18] Gateway Earth is a major part of this solution.

It is unlikely The Gateway Earth Architecture would be either accepted or be effective at one position in GEO. In GEO the transfer times and fuel requirements would be at least double for moving satellites around GEO compared to moving from GEO to Gateway Earth in a higher orbit. An orbit 150km higher has low transfer times, ~12 hours, low fuel requirements, from ~7.5kg for ion rocket engines to ~30kg for chemical rocket engines, and is far enough away from GEO and graveyard orbits to be at a very low risk of collision. In this orbit it would be able to access all GEO, GSO and graveyard satellites creating an almost *inexhaustible* revenue and resource stream.

Repurposed solar panels would be relatively straightforward to integrate into Gateway Earth’s power grid and studies have shown that power degradation after 15 years is at worst 0.8% per year leaving the majority of them at around 25% efficient. This would save millions in construction costs and would turn into a revenue stream once construction is finished. Although detailed studies have not been carried out, cameras could be used to build optical interferometers for exoplanet and Near Earth Object observations.

Refueling of GEO satellites should be avoided and Space Drones, such as Effective Spaces and orbital ATK’s, must be used for station keeping and orbital transfers when satellite cannot move of their own accord.

NEXT STEPS

- The legal framework for operating 150km away from GEO needs addressing and models of how the GEDG could work with partners to reduce GEO debris and service, repurpose or recycle satellites.
- A reassessment of the debris risk at GEO, GEO graveyard and between.
- Calculation tool improved to calculate Z-corrections or detailed information from service providers (Drones)
- The testing of old solar panels of various power outputs through new power regulators needs to be reviewed and tests need to be completed to find the safest and most cost effective solution to reusing solar panels.
- Camera interferometers need building and testing on Earth from working engineering model cameras of GEO satellites to find the most effective solution for astronomical observations.

- The viability of grinding down space grade aluminium, and other materials, in a vacuum for use in additive manufacturing so they are suitable as materials for additive manufacturing of new orbital or interplanetary craft needs assessing. If the grade of material is such that it would not be useable as an additive manufacturing material for spacecraft then it could be used as radiation and micrometeorite/debris shielding, in a similar way to the ESA Moon base printed shielding from Luna regolith. [37]

ACKNOWLEDGMENTS

The GEDG has been a source of much inspiration and advice through this project. I would like to thanks Matjaz Vidmar and Katy Voisy from GEDG directly for their support, Shahida Barick from Effective space for information and guidance on GEO operation, David Hann from the University of Nottingham for funding BIS conference attendance. Finally from the University of Nottingham I would like to thank Paul Bhatia, Chantal Cappelletti, Shirley Ashcroft-Frost, Tom Westby, Catherine Collett, Mohamed Elmaghrbi, Iain Patterson Stevens and Francesco Piga for all the support with calculations, MATLAB, proofreading and orbital theories.

REFERENCES:

1. Webber. D. (2015). "Gateway Earth" – Low Cost Access to Interplanetary Space. *Proceedings of the 13th Reinventing Space Conference*.

2. Weber. D. (2014). Bridgehead – Interplanetary Travel Becomes Routine. Proceedings of the *IAA Space Exploration Conference*.

3. Vidmar. M & Weber. D. (2017). A Pragmatic Modular Architecture for Space Access and Exploration. *Proceedings of 68th International Astronautical Congress (IAC).*

4. Vidmar. M, Et.Al. (2017). Developing the Technical and Operational Framework for Gateway Earth Space Access Architecture. *Proceedings of 15th Reinventing Space Conference.*

5. Molitch-Hou. M. (2017). *One Small Step for 3D Printing Satellites in the Vacuum of Space.* Available: https://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/15455/One-Small-Step-for-3D-Printing-Satellites-in-the-Vacuum-of-Space.aspx . Last accessed 7/10/18.

6. Nogales. C, Et Al. (2017). MakerSat-0: 3D-Printed Polymer Degradation First Data from Orbit. *Proceedings of the 32nd Annual Small Satellite Conference*.

7. Medium. (2017). *Dream on Earth. Build among the stars.* Available: https://medium.com/made-in-space/new-space-based-manufacturing-technologies-demonstrated-by-made-in-space-79000e771ac4 . Last accessed 7/10/18.

8. Wikipedia. (2018). *Sidereal Time.* Available: https://en.wikipedia.org/wiki/Sidereal_time . Last accessed 14/10/18.

9. NIST. (2018). *Fundamental Physical constants.* Available: https://physics.nist.gov/cgi-bin/cuu/Value?bg|search_for=abbr_in! . Last accessed 24/6/18.

10. International Earth Rotation and Reference Systems Service. (~2008). General definitions and numerical standards. *IERS Technical Note*. 36, 15-20.

11. Longstaff. R & Hempsell. M. (2017). A MISSION TO DEMONSTRATE THE PRESERVATION OF THE GEOSTATIONARY ORBIT. *Proceedings of the 7th European Conference on Space Debris*.

12. Sam Jarman. (2018). *Space drones will give satellites a new lease of life.* Available: https://physicsworld.com/a/space-drones-will-give-satellites-a-new-lease-of-life/ . Last accessed 26/1/18.

13. ESA. *INTRODUCING GOCE.* Available: https://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Introducing_GOCE . Last accessed 15/9/18.

14. Hirt. C, Et Al. (2013). Geophysical Research Letters. *New ultra-high resolution picture of Earth's gravity field*. 40 (16).

15. Borissov. S, Wu. Y & Mortari. D. (2015). East–West GEO Satellite Station-Keeping with Degraded Thruster Response. *Aerospace*. (2), 681-601.

16. Amos. J. (2011). *International Space Station in debris scare.* Available: https://www.bbc.co.uk/news/science-environment-13949956 . Last accessed 25/4/18.

17. Inter-Agency Space Debris Coordination Committee. (2014). Support to the IADC Space Debris Mitigation Guidelines. 04 (06).

18. Ostrove. B (2015). *Average Commercial Communications Satellite Launch Mass Declines, Again.* Available: https://blog.forecastinternational.com/wordpress/average-commercial-communications-satellite-launch-mass-declines-again/ . Last accessed 28/9/18.

19. Dvornychenko, V. (1990). The generalized Tsiolkovsky equation. *National Institute of Standards and Technology*. 449-457.

20. European Space Operations Centre (2018). ESA’s Annual Space Environment Report. *ESA Space Debris Office*. 2.

21. Weedon, B. (2010). *Dealing with Galaxy 15: Zombiesats and on-orbit servicing.* Available: http://thespacereview.com/article/1634/1 . Last accessed 10/12/17.

22. United Nations. (2008). United Nations Treaties and Principles on Outer Space. *UNITED NATIONS OFFICE FOR OUTER SPACE AFFAIRS*. 2.

23. ESA. (2011(updated)). *THE GEOSTATIONARY SERVICING VEHICLE* . Available: https://www.esa.int/Our_Activities/Space_Engineering_Technology/Automation_and_Robotics/The_Geostationary_Servicing_Vehicle_GSV . Last accessed 20/8/18.

24. Lothar Gerlach. (2009). *INSIDE A SOLAR CELL.* Available: https://www.esa.int/Our_Activities/Space_Engineering_Technology/Inside_a_solar_cell . Last accessed 28/9/18.

25. Rodiek, J & Brandhorst, H. (2008). SOLAR ARRAY RELIABILITY IN SATELLITE OPERATIONS. *Acta Astronautica*. 63 (11).

26. SpaceX. (2018). *CAPABILITIES AND SERVICES* . Available: https://www.spacex.com/about/capabilities . Last accessed 1/9/18.

27. NASA. (UPDATED 2017). *About the Space Station Solar Arrays.* Available: https://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays-about.html . Last accessed 27/9/18.

28. Boeing. (2018). *Cells & CICs.* Available: https://www.spectrolab.com/photovoltaics.html . Last accessed 20/7/18.

29. Northrop Grumman Corporation. (2018). *Ultraflex Factsheet.* Available: https://www.northropgrumman.com/Capabilities/SolarArrays/Documents/UltraFlex_Factsheet.pdf . Last accessed 20/7/18.

30. ESA. (2016). *Tim and Tim Safely Back in Space Station After Spacewalk.* Available: https://www.esa.int/Our_Activities/Human_Spaceflight/Principia/Tim_and_Tim_safely_back_in_Space_Station_after_spacewalk . Last accessed 27/9/18.

31. McNelis, A, et al.. (2014). Simulation and Control Lab Development for Power and Energy Management for NASA Manned Deep Space Missions. *Proceedings of the 50th AIAA/ASME/SAE/ASEE Propulsion and Energy Forum and Exposition*.

32. OSCAR . (2015). *Satellite: GOES 11*. Available: https://www.wmo-sat.info/oscar/satellites/view/147 . Last accessed 27/9/18.

33. ANON. (LAST UPDATED 2018). *WIDE ANGLE SEARCH FOR PLANETS.*Available: https://en.wikipedia.org/wiki/Wide_Angle_Search_for_Planets . Last accessed 28/9/18.

34. Borgmeyer, S. (2018). *ORBITAL PROPULSION FLUIDIC EQUIPMENT.* Available: http://www.space-propulsion.com/brochures/valves/space-propulsion-valves.pdf

35. OSCAR . (2015). *Satellite: DMSP-F13* . Available: https://www.wmo-sat.info/oscar/satellites/view/60 . Last accessed 27/9/18.

36. STEVEN CLARK. (2015). *DMSP satellite's break-up linked to battery failure.* Available: https://spaceflightnow.com/2015/07/24/dmsp-satellites-break-up-linked-to-battery-failure/ . Last accessed 27/9/18.

37. ESA. (2013). *BUILDING A LUNA BASE WITH 3D PRINTING.* Available: http://www.esa.int/Our_Activities/Space_Engineering_Technology/Building_a_lunar_base_with_3D_printing . Last accessed 20/2/18.